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Method for compensation for a zero error in a Coriolis gyro

The invention relates to a method for compensation for a zero error in a Coriolis gyro.

Coriolis gyros (also referred to as vibration gyros) are being used increasingly for navigation purposes. Coriolis gyros have a mass system which is caused to oscillate. This oscillation is generally a superimposition of a large number of individual oscillations. These individual oscillations of the mass system are initially independent of one another and can each be referred to abstractly as "resonators". At least two resonators are required for operation of a vibration gyro: one of these resonators (the first resonator) is artificially stimulated to oscillate, and this is referred to in the following text as the "stimulating oscillation". The other resonator (the second resonator) is stimulated to oscillate only when the vibration gyro is moved/rotated. This is because Coriolis forces occur in this case, which couple the first resonator to the second resonator, absorb energy from the stimulating oscillation for the first resonator, and transfer this to the read oscillation of the second resonator. The oscillation of the second resonator is referred to in the following text as the "read oscillation". In order to determine movements (in particular rotations) of the Coriolis gyro, the read oscillation is tapped off, and a corresponding read signal (for example the read oscillation tapped-off signal) is investigated to determine whether any changes have occurred in the amplitude of the read oscillation, which represent a measure of the rotation of the Coriolis gyro. Coriolis gyros may be implemented both as open-loop systems and as closed-loop systems. In a closed-loop system, the amplitude of the read oscillation is continuously reset to a

fixed value - preferably zero - via respective control loops.

One example of a closed-loop version of a Coriolis gyro will be described in the following text, with reference to Figure 2, in order to illustrate further the method of operation of a Coriolis gyro.

A Coriolis gyro 1 such as this has a mass system 2 which can be caused to oscillate and is also referred to in the following text as a "resonator". A distinction must be drawn between this expression and the "abstract" resonators mentioned above, which represent individual oscillations of the "real" resonator. As already mentioned, the resonator 2 may be regarded as a system composed of two "resonators" (the first resonator 3 and the second resonator 4). Both the first and the second resonator 3, 4 are each coupled to a force sensor (not shown) and to a tapping system (not shown). The noise which is produced by the force sensor and the tapping systems is indicated schematically here by Noise1 (reference symbol 5) and Noise2 (reference symbol 6).

The Coriolis gyro 1 furthermore has four control loops:

A first control loop is used to control the stimulating oscillation (that is to say the frequency of the first resonator 3) at a fixed frequency (resonant frequency). The first control loop has a first demodulator 7, a first low-pass filter 8, a frequency regulator 9, a VCO (Voltage Controlled Oscillator) 10 and a first modulator 11.

A second control loop is used to control the stimulating oscillation at a constant amplitude, and has a second demodulator 12, a second low-pass filter 13 and an amplitude regulator 14.

A third and a fourth control loop are used to reset those forces which stimulate the read oscillation. In this case, the third control loop has a third demodulator 15, a third low-pass filter 16, a quadrature regulator 17 and a third modulator 22. The fourth control loop contains a fourth demodulator 19, a fourth low-pass filter 20, a rotation rate regulator 21 and a second modulator 18.

The first resonator 3 is stimulated at its resonant frequency 1. The resultant stimulating oscillation is tapped off, is phase-demodulated by means of the first demodulator 7, and a demodulated signal component is supplied to the first low-pass filter 8, which removes the sum frequencies from it. The tapped-off signal is also referred to in the following text as the stimulating oscillation tapped-off signal. An output signal from the first low-pass filter 8 is applied to a frequency regulator 9, which controls the VCO 10 as a function of the signal supplied to it, such that the in-phase component essentially tends to zero. For this purpose, the VCO 10 passes a signal to the first modulator 11, which itself controls a force sensor such that a stimulating force is applied to the first resonator 3. If the in-phase component is zero, then the first resonator 3 oscillates at its resonant frequency 1. It should be mentioned that all of the modulators and demodulators are operated on the basis of this resonant frequency 1.

The stimulating oscillation tapped-off signal is also supplied to the second control loop and is demodulated by the second demodulator 12, whose output is passed through the second low-pass filter 13, whose output signal is in turn supplied to the amplitude regulator 14. The amplitude regulator 14 controls the first modulator 11 as a function of this signal and of a

nominal amplitude sensor 23, such that the first resonator 3 oscillates at a constant amplitude (that is to say the stimulating oscillation has a constant amplitude).

As has already been mentioned, Coriolis forces - indicated by the term FC·cos(1·t) in the drawing - occur on movement/rotation of the Coriolis gyro 1, which couple the first resonator 3 to the second resonator 4, and thus cause the second resonator 4 to oscillate. A resultant read oscillation at the frequency 2 is tapped off, so that a corresponding read oscillation tapped-off signal (read signal) is supplied to both the third and the fourth control loop. In the third control loop, this signal is demodulated by the third demodulator 15, sum frequencies are removed by the third low-pass filter 16, and the low-pass-filtered signal is supplied to the quadrature regulator 17, whose output signal is applied to the third modulator 22 so as to reset corresponding quadrature components of the read oscillation. Analogously to this, in the fourth control loop, the read oscillation-tapped-off signal is demodulated by the fourth demodulator 19, passes through the fourth low-pass filter 20, and a correspondingly low-pass-filtered signal is applied on the one hand to the rotation rate regulator 21, whose output signal is proportional to the instantaneous rotation rate, and is passed as a rotation rate measurement result to a rotation rate output 24, and on the other hand to the second modulator 18, which resets corresponding rotation rate components of the read oscillation.

A Coriolis gyro 1 as described above may be operated both in a double-resonant form and in a non-double-resonant form. If the Coriolis gyro 1 is operated in a double-resonant form, then the frequency 2 of the read oscillation is approximately equal to the frequency 1

of the stimulating oscillation while, in contrast, in the non-double-resonant case, the frequency 2 of the read oscillation is different from the frequency 1 of the stimulating oscillation. In the case of double resonance, the output signal from the fourth low-pass filter 20 contains corresponding information about the rotation rate while, in contrast, in the non-double-resonant case, the output signal from the third low-pass filter 16. In order to switch between the different double-resonant/non-double-resonant operating modes, a doubling switch 25 is provided, which selectively connects the outputs of the third and the fourth low-pass filter 16, 20 to the rotation rate regulator 21 and the quadrature regulator 17.

As a result of unavoidable manufacturing tolerances, it is necessary to take account of slight misalignments between the stimulating forces/resetting forces/force sensors/taps and the natural oscillations of the resonator 2 (that is to say the real stimulating and reading modes of the resonator 2). This means that the read oscillation tapped-off signal is subject to errors. In a situation such as this, the read oscillation tapped-off signal is thus composed of a part which originates from the real read oscillation, and of a part which originates from the real stimulating oscillation. The undesired part causes a Coriolis gyro zero error whose magnitude, however, is unknown, since it is impossible to distinguish between these two parts when the read oscillation tapped-off signal is tapped off.

The object on which the invention is based is to provide a method which allows the zero error described above to be determined.

This object is achieved by the method as claimed in the features of patent claim 1. The invention also

provides a Coriolis gyro as claimed in patent claim 6. Advantageous refinements and the developments of the idea of the invention can be found in the respective dependent claims.

According to the invention, in the case of a method for determination of a zero error of a Coriolis gyro, the frequency (preferably the resonant frequency) of the read oscillation is modulated, the output signal from a rotation rate control loop or quadrature control loop for the Coriolis gyro is demodulated in synchronism with the modulation of the frequency (resonant frequency) of the read oscillation in order to obtain an auxiliary signal which is a measure of the zero error. A compensation signal is then produced, and is passed to the input of the rotation rate control loop or quadrature control loop, with the compensation signal being controlled such that the magnitude of the auxiliary signal is as small as possible.

In this case, the expression "resonate", means the entire mass system of the Coriolis gyro that can be caused to oscillate, that is to say with reference to Figure 2, that part of the Coriolis gyro which is identified by the reference number 2.

One major discovery on which the invention is based is that the output signal from the rotation rate control loop/quadrature control loop changes as a result of a change in the frequency of the read oscillation only when there is a corresponding zero error, that is to say when misalignments exist between the stimulating forces/resetting forces/force sensors/taps and the natural oscillations of the resonator. Thus, if a compensation signal which compensates for the zero error in the read oscillation tapped-off signal caused by misalignments is passed to the input of the rotation rate control loop/quadrature control loop or directly

to the read oscillation tapped-off signal, then the output signal from the rotation rate control loop/quadrature control loop does not change any more either in the event of a change in the frequency (in particular a change in the resonant frequency) of the read oscillation. Since the change in the output signal from the rotation rate control loop/quadrature control loop is recorded by the auxiliary signal, the zero error can be determined and compensated for as follows: the compensation signal is controlled such that the auxiliary signal (and thus the change in the output signal from the control loop) is as small as possible.

The frequency (resonant frequency) of the read oscillation is preferably modulated with zero mean value, for example at 55 Hz.

The auxiliary signal is preferably low-pass filtered, and the compensation signal is produced on the basis of the low-pass-filtered auxiliary signal. The compensation signal may be produced, for example, by multiplication of a controlled signal, which is produced on the basis of the auxiliary signal, by a signal which originates from an amplitude regulator for controlling the amplitude of the stimulating oscillation. The auxiliary signal is preferably determined from the output signal from the quadrature control loop, and the compensation signal is passed to the input of the rotation rate control loop.

The invention also provides a Coriolis gyro which is characterized by a device for determination of the zero error of the Coriolis gyro, having:

- a modulation unit which modulates the frequency of the read oscillation of the Coriolis gyro,
- a demodulation unit, which demodulates the output signal from a rotation rate control loop or quadrature

control loop of the Coriolis gyro in synchronism with the modulation of the frequency of the read oscillation, in order to obtain an auxiliary signal which is a measure of the zero error, and

- a control unit, which produces a compensation signal and passes this to the input of the rotation rate control loop or quadrature control loop, with the control unit controlling the compensation signal such that the auxiliary signal is as small as possible.

The invention will be described in more detail in the form of an exemplary embodiment in the following text, with reference to the accompanying figures in which:

Figure 1 shows the schematic design of a Coriolis gyro which is based on the method according to the invention;

Figure 2 shows the schematic design of a conventional Coriolis gyro;

Figure 3 shows a sketch in order to explain the interaction of the resonator, force sensor system and tapping system in a Coriolis gyro;

Figures 4a to 4d show a sketch in order to explain the forces and oscillation amplitudes for a Coriolis gyro at double resonance;

Figures 5a to 5d show a sketch in order to explain the forces and oscillation amplitudes for a Coriolis gyro close to double resonance;

Figures 6a to 6d show a sketch in order to explain the method according to the invention at double resonance.

Figures 7a to 7d show a sketch in order to explain the

method according to the invention close to double resonance.

Parts and devices which correspond to those from Figure 2 are annotated with the same reference symbols in the drawings, and will not be explained again.

First of all, the general method of operation of a Coriolis gyro will be explained once again on the basis of Figures 3 to 5, in the form of a vector diagram illustration (Gaussian number plane).

The method according to the invention operates only when double resonance is essentially present on average. The drawings which are annotated with "close to double resonance" show the changed conditions when the situation of "close to double resonance" occurs as a result of modulation of the resonant frequency of the read oscillation.

Figure 3 shows, schematically, a Coriolis gyro, to be more precise a system 40 comprising a resonator (not shown), a force sensor system 41 and a tapping system 42 in a Coriolis gyro. Possible oscillations x (stimulation) and y (read) are also indicated, which are coupled to one another by Coriolis forces in the event of rotations at right angles to the plane of the drawing. The x oscillation (complex; purely imaginary at resonance) is stimulated by the alternating force with the complex amplitude Fx (in this case only the real part Fxr). The y oscillation (complex) is reset by the alternating force of the complex amplitude Fy with the real part Fyr and the imaginary part Fyi. The rotation vectors exp(i* *t) are in each case omitted.

Figures 4a to 4d show the complex forces and complex oscillation amplitudes for an ideal Coriolis gyro with the same resonant frequency for the x and y

oscillations (double resonance). The force Fxr is controlled so as to produce a purely imaginary, constant x oscillation. This is achieved by an amplitude regulator 14, which controls the magnitude of the x oscillation, and by a phase regulator 10/frequency regulator 9, which controls the phase of the x oscillation. The operating frequency 1 is controlled such that the x oscillation is purely imaginary, that is to say the real part of the x oscillation is controlled to be zero.

The Coriolis force during rotation, FC, is now purely real, since the Coriolis force is proportional to the speed of the x oscillation. If both oscillations have the same resonant frequency, then the y oscillation, caused by the force FC, has the form illustrated in Figure 4d. If the resonant frequencies of the x and y oscillations differ slightly, then complex forces and complex oscillation amplitudes occur, with the form as shown in Figures 5a to 5d. In particular, this results in a y oscillation, stimulated by FC, as shown in Figure 5d.

When double resonance is present, the real part of the y tapped-off signal is zero but, in contrast, it is not zero in the absence of double resonance. In both cases, with reset gyros, the Coriolis force FC is zeroed by a regulator Fyr, which compensates for FC. In the case of Coriolis gyros which are operated with double resonance, the imaginary part of y is zeroed by means of Fyr, and the real part of y is zeroed by means of Fyi. The bandwidth of the two control processes is approximately 100 Hz.

The method according to the invention will now be explained in more detail, using an exemplary embodiment, with reference to Figure 1.

A resetting Coriolis gyro 1' is additionally provided with a demodulation unit 26, a fifth low-pass filter 27, a control unit 28, a modulation unit 29 and a first multiplier 30 or, alternatively a second multiplier 31.

The modulation unit 29 modulates the frequency of the read oscillation of the resonator 2 at a frequency mod. An output signal from the quadrature control loop is supplied to the demodulation unit 26, which demodulates this signal in synchronism with the frequency mod in order to obtain an auxiliary signal. If there is any zero error (that is to say if there are any misalignments between the stimulating forces/resetting forces/force sensors/taps and the natural oscillations of the resonator 2) then the strength of the auxiliary signal varies as a function of the frequency of the read oscillation. The auxiliary signal is supplied to the fifth low-pass filter 27, which produces a low-pass-filtered signal and supplies this to the control unit 28. The control unit 28 uses the low-pass-filtered auxiliary signal as the basis for producing a signal which is emitted to the first multiplier 30. This multiplies the signal emitted from the control unit 28 by a signal which originates from the amplitude regulator 14 for controlling the amplitude of the stimulating oscillation. A compensation signal, which is obtained from the multiplication process, is added to the input to the rotation rate control loop. The control unit 28 controls the signal supplied to the first multiplier 30 such that the magnitude of the auxiliary signal is as small as possible. This corrects the zero error. Furthermore, the magnitude of the zero error can be determined by the compensation signal, which represents a measure of the zero error. Alternatively, the output signal from the control unit 28 can be supplied to the second multiplier 31, which multiples this signal by the stimulating oscillation tapped-off signal and adds

a compensation signal, which is produced in this way, to the read oscillation tapped-off signal. The expression "control unit" is not restricted to the control unit 28 but may also mean the combination of the control unit 28 and the first or second multiplier 30, 31.

The signal which is supplied to the demodulation unit 26 may alternatively be tapped-off at a different point within the control loops, as well.

The method according to invention that has just been described can also be illustrated as follows, with reference to Figures 6a to 6d and 7a to 7d:

The tap for the y oscillation (second resonator x2, 4) in general also "sees" a part of the x oscillation (first resonator x1, 3): a21*x. This results in a Coriolis gyro zero error, which must be determined. Figures 6a to 6d show the situation at double resonance, while Figures 7a to 7d show the situation close to double resonance. In both cases, the sum signal of the actual y movement and a21*x is "zeroed" by means of Fyi and Fyr. If a21 is not equal to zero, Fxr is not equal to zero when the rotation rate is zero (zero error). Fyi becomes zero only when double resonance is present. A quadrature bias results when there are discrepancies in the resonant frequencies.

The compensation for a21 is now carried out, according to the invention, as follows. The gyro is assumed to be at double resonance. The resonant frequency of the read oscillation, which can be detuned electronically, is modulated by the modulation unit 29 with a zero mean value (for example at 55 Hz), and the signal Fyi is demodulated by the demodulation unit 26 in synchronism when the resetting control loops are closed. If a21 were zero, then Fyi would not vary with the frequency,

that is to say it changes only in the situation where a21 is not equal to zero. In the latter case, the low-pass-filtered, synchronously demodulated Fyi signal is not equal to zero. The demodulated signal is supplied to the control unit 28 (preferably in the form of software), which controls a factor a21comp (auxiliary variable). A controlled component of the x movement, a21comp*x, is tapped off from the signal at the y tap (preferably in software). The magnitude of this component a21comp is controlled such that the demodulated Fyi signal becomes zero. There is therefore no longer any x signal component in the signal from the y tap that has been cleaned in this way, and the bias caused by the read cross-coupling disappears. At double resonance and with the same Q factors, just a cross-coupling regulator on its own would zero the bias caused by the read cross-coupling. This is because the modulation of Fxr also slightly modulates the amplitude of x. The sum of the force component of x in Fyr and the read component of x at the y tap is thus zeroed via the force cross-coupling regulator. The bias thus disappears if the Q factor is the same.

Alternatively, it is also possible to use noise to modulate the read oscillation. Appropriate synchronous demodulation of the noise component in the read signal is used in a situation such as this.